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ABSTRACT

Separation and removal of asphalt binder from aggregate surface due primarily to the action of moisture and/or moisture vapor is generally termed "stripping." In the identification of the cause of stripping practitioners have, historically, tended to focus their attention on the sensitivity of the aggregate and asphalt system in the presence of moisture. The authors classify this stripping as a physio-chemical incompatibility of the asphalt system, and the classical moisture sensitivity tests are relevant.

The case histories in this paper document the effect of pavement saturation. The authors suggest that under saturated conditions all asphalt mixes may fail as a consequence of cyclical hydraulic stress physically scouring the asphalt binder from the aggregate. The authors classify this stripping as a mechanical failure of the asphalt pavement system, and the classical moisture sensitivity tests are irrelevant. While under saturated conditions a less moisture sensitive asphalt system may survive longer, it is probable that failure is deferred and not avoided.

Stripping became a major problem in the United States in the late 1970s. Premature failures of asphalt overlays within two years of construction are not uncommon. This paper documents four such case histories from Pennsylvania, Oklahoma, and New South Wales in Australia.

Case histories give the details of construction, visual observation of pavement distress, sampling and testing of pavement, and conclusions/recommendations. Moisture profile within the pavement structure was also determined by dry sampling with a jack hammer. The phenomenon of stripping was investigated from a global perspective, looking at the relative permeability of the pavement components, subsurface drainage system, and the interaction between different asphalt courses including open-graded friction courses.

Hypotheses are presented to explain the mechanisms that will result in the pavement saturation observed. Recommendations have been made to minimize instances of such premature failures resulting from stripping.

KEY WORDS: Stripping, asphalt overlays, hot mix asphalt, asphalt concrete, moisture damage, case histories, moisture content, saturation

PREMATURE FAILURE OF ASPHALT OVERLAYS FROM STRIPPING: CASE HISTORIES

Prithvi S. Kandhal and Ian J. Rickards

INTRODUCTION

The term "stripping" is applied to hot mix asphalt (HMA) mixtures that generally exhibit separation and removal of asphalt binder film from aggregate surfaces due primarily to the action of moisture and/or moisture vapor. Although stripping of HMA has been mentioned sporadically in the literature since early twentieth century, it became a major problem in the U.S. in the late 1970s. Several HMA related developments took place in the 1970s, which may or may not have contributed to the onset of stripping problems in the U.S. It may be interesting to list some of these developments as follows:

- The 1972 Clean Air Act required baghouses in HMA plants to collect fines which are partially or fully added back to the mix. Prior to 1972, these very fine dust particles were released into the atmosphere and were not incorporated in the mix.
- Many crude oil sources changed in 1973 due to the Arab Oil Embargo. Although not proven, some people believe that the quality of some asphalt binders changed.
- Drum mixers came into use in HMA plants, which dried the aggregate and mixed it with asphalt binder in the same drum.
- Vibratory rollers became common and the use of pneumatic tired rollers for intermediate compaction was mostly phased out. Some asphalt paving technologists believe the pneumatic tired rollers are helpful in sealing the fresh HMA mat (thus making it almost impermeable at the surface) due to kneading action.
- The use of open-graded friction course (OGFC) or plant mixed seal coats became common in some states. The Federal Highway Administration encouraged the use of OGFC to improve the skid resistance of HMA wearing courses.
- The use of siliceous aggregates which are relatively more prone to stripping, increased to obtain increased skid resistance in HMA pavements.
- PCC pavements on interstates built in the 1950s increasingly required asphalt overlays in the 1970s. The subsurface drainage of PCC pavements was generally inadequate. Overlaying the 4-lane PCC pavements along with paving the shoulders and median created a very wide asphalt surface trapping the moisture and/or moisture vapor (1).
- Asphalt contents in HMA mixtures generally decreased (reducing binder film thickness) to obtain increased rut resistance.
- Last but a very important factor, truck traffic (and tire pressures) had increased substantially on interstate and primary highways by 1970s and continues to increase.

Although the stripping problem is prevalent in most of the United States, it is puzzling to note that it has not been identified as a major problem in the northeastern United States where a wide variety of aggregates (including siliceous aggregates) and asphalt binder sources are used.

Numerous papers have been published during the last 20 years on the possible causes of stripping, methods for predicting stripping potential of HMA mixtures, and use of antistripping agents to minimize or prevent stripping. However, very few papers are available in the literature, which have evaluated this phenomenon considering the pavement permeability and drainage in the total highway pavement system or the interaction between different HMA courses including open-graded friction courses. This paper presents four field case histories where premature failure of HMA pavement occurred due to stripping. The four projects in Pennsylvania, Oklahoma (two), and New South Wales, Australia were investigated by the first author. The second author was co-investigator for the Australian project. Unlike wet coring which is commonly used, HMA pavement layers were sampled with a jack hammer without adding any water. The actual moisture profiles obtained in HMA pavements, which are generally not found in the literature, have been reported. Thus, the stripping phenomenon in a specific HMA course has not been evaluated in isolation but in the context of the total pavement system. The discussion of four case histories follows. In all cases, critical asphalt pavement layers were substantially saturated and this is believed to have preceded the resulting stripping.

PENNSYLVANIA TURNPIKE (CUMBERLAND COUNTY)

Pennsylvania Turnpike Mile Post (MP) 209.5 to 218.0 received an asphalt overlay consisting of 37 mm thick ID-2 wearing course (it is a dense-graded 9.5 mm nominal size mix) in 1994. The percentage of material passing 4.75, 2.36, and 0.075 mm was 71, 45, and 4.5 percent, respectively, with a design asphalt content of 6.3 percent. The overlay consisting of crushed gravel aggregate HMA mixture was placed during the period of April-November 1994 after milling the existing road surface to an average depth of 40 mm. This project started to exhibit premature pavement distress in 1996 primarily on the westbound (W.B.) slow lane from MP 215.5 to 218.0. The section from MP 209.5 to 215.5 did not develop any significant pavement distress. The project was inspected in July 1996 to investigate the probable cause of the distress. The following observations were recorded during the inspection.

Typical telltale signs of moisture-induced stripping: fines brought up to the surface by water (mud stains), flushing of the surface, and potholing, were clearly visible on the W.B. slow lane from MP 215.5 to 218.0 (Figure 1). Potholes had developed in both wheel tracks of the W.B. slow lane between MP 215.5 and 218.0. There were more potholes in the inside wheel track compared to the outside wheel track (Figure 2). Rutting of the pavement had also started to develop in many areas (Figure 3). A similar investigation of an adjacent section of the Pennsylvania Turnpike between MP 218 and 226 was conducted by the first author in 1978 (1). On that project, the potholing was primarily occurring in the inside wheel track of the slow lane and rutting associated with stripping was not a significant problem. Therefore, this project was exhibiting more severe distressed condition than the 1978 project.

Sampling of Pavement and Observations

It appeared prudent to sample the pavements in the distressed area (MP 215.5 to 218.0) as well as in the relatively good area (MP 215.5 to 209.5) of this project. Such investigative methodology has been recommended to establish the cause of stripping (2, 3). A jack hammer was used to cut out approximately 500 mm x 500 mm holes so that each pavement layer could be sampled for testing and visual examination in the existing condition without adding any water. One hole each was cut in the inside wheel track, between the wheel tracks, and the outside wheel track of the westbound slow lane at MP 217.65 in the distressed area (Figure 4). Each layer was observed and sampled to determine the moisture content and the maximum theoretical specific gravity of the asphalt mix.

Figure 5 shows the two top layers of the pavement: the new gravel wearing course and the old limestone binder course. The old limestone binder course was about 80% stripped with bare rock particles and hardly any cohesion. This course had a lot of cavities and free moisture (Figure 5). The new gravel wearing course had started to strip from the bottom upwards (about 50% stripping) and one could see the migrated asphalt binder at the top of this layer. It was evident that the excessive moisture or water in the old limestone binder course was causing the stripping in the new gravel wearing course because of the excessive pore pressure buildup under traffic in the slow lane.

Figure 1. General view of the distressed westbound lane near MP 217.65 showing mud stains, flushing, and potholes.

Figure 2. Potholes in both wheel tracks of the distressed westbound slow lane near MP 217.65 (most potholes in the inside wheel track).

Figure 3. Potholes and rutting in the westbound slow lane near MP 217.65.

Figure 4. Three square holes cut in the westbound slow lane at MP 217.65.

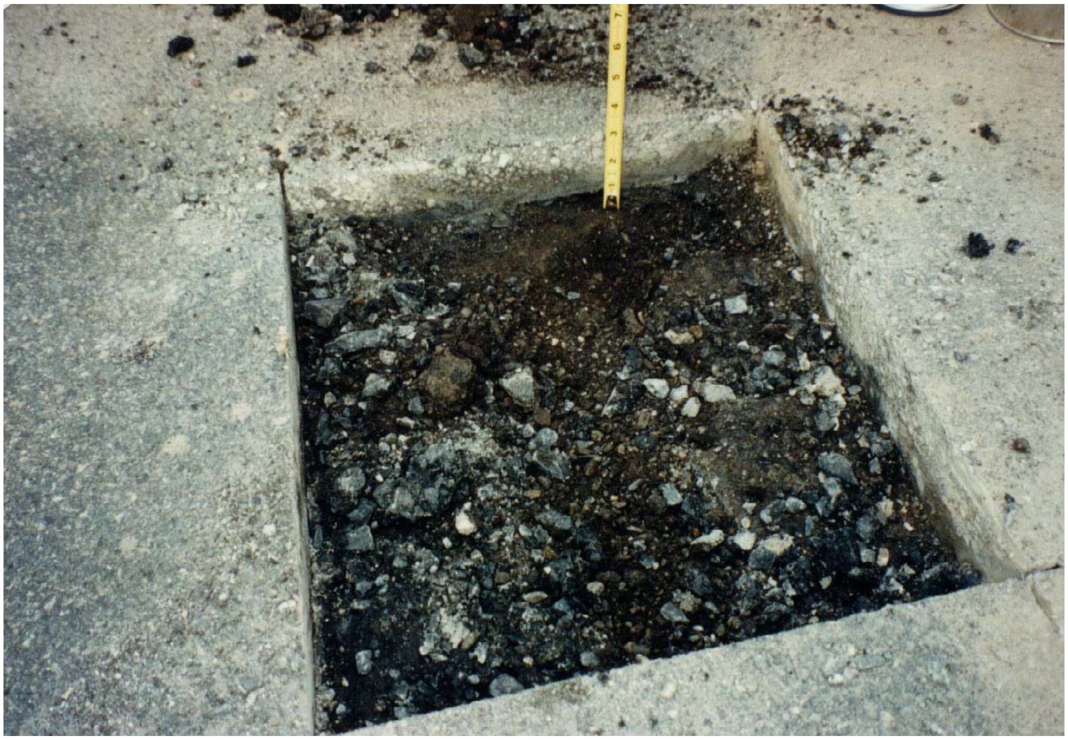


Figure 5. Hole exposing new gravel wearing course and underlying old limestone binder course at MP 217.65.

Figure 6 shows the hole cut out full depth about 200 mm to the existing PCC pavement. It was observed that the old gravel wearing course underlying the old limestone binder course was also saturated with water, about 50% stripped, and very friable. It was hard to imagine that such a friable mix (with almost no cohesion) was existing at a depth of about 75 mm only from the road surface. Figure 6 clearly shows wetness in the old limestone binder course as well as in the old gravel wearing course.

Table 1 gives a summary of observations made for each layer in the holes cut in the distressed area at MP 217.65. The table shows there are five HMA courses on the PCC pavement including the new gravel wearing course placed at different times in the past. The old slag wearing course underlying the old gravel wearing course was moist but the stripping was observed to be minimal. However, for reasons unknown, the old second limestone binder course underlying the old slag wearing course was only partially stripped. The existing PCC pavement surface was very wet.

It was quite evident from some mud stains in asphalt overlays that water was coming from underneath the PCC pavement primarily through the longitudinal and transverse joints, cracks in the PCC pavement and disintegrated concrete itself at some places. It was also possible, as observed in the 1978 investigations (1) that moisture was being drawn from the subbase under the paved median into the asphalt overlay layers probably in the form of moisture vapor during the heat of the day. At that time, all four lanes of the Turnpike, the median, and shoulders were paved with HMA which created a 22-25 m wide asphalt surface with no outlet for moisture or moisture vapor. Moisture vapor accumulated in the pavement layers during the day condenses during the night until the asphalt pavement layers become saturated with water. With saturation the pore water pressure developed by differential thermal expansion and cyclic stresses from the traffic (compressing the pavement) ruptures the asphalt-aggregate bond causing stripping.

Figure 6. Hole exposing all asphalt concrete layers and PCC surface at MP 217.65.

Table 1. Visual Observations of Holes at MP 217.65 in Westbound Slow Lane

Pavement Layer	Inside Wheel Track (IWT)	Between Wheel Tracks (BWT)	Outside Wheel Track (OWT)
New Gravel Wearing Course	Moist, stripping at the bottom (50%), excess asphalt binder can be seen migrating toward the surface	Observations similar to IWT except mix was moist to wet and stripping was about 40%	Observation similar to IWT
Old Limestone Binder Course	Very wet, badly stripped (80%), bare aggregate particles give an appearance of a French drain	Observations similar to IWT	Observation similar to IWT
Old Gravel Wearing Course	Moist to wet, stripped (50%), mix is very friable, can be broken with hand	Observations similar to IWT	Observation similar to IWT
Old Slag Wearing Course	Moist, minimal stripping	Observations similar to IWT	Observation similar to IWT
Old Limestone Binder Course	Wet, partly stripped	Observations similar to IWT	Observation similar to IWT
Concrete	Wet	Observations similar to IWT	Observation similar to IWT

Based on the experience from the 1978 investigations it was highly likely that the old limestone binder course and the old gravel wearing course were already partially stripped when the new overlay was placed in 1994. Therefore, the water in these two stripped layers started to strip the new gravel wearing course from bottom upwards immediately after its placement. Figure 7 shows from left to right: new gravel wearing course with stripping at the bottom; old limestone binder course, wet and very badly stripped; and the old gravel wearing course, wet and very friable.

Figure 7. From left to right: new gravel wearing course, old limestone binder course, and old gravel wearing course, from a hole at MP 217.65.

Full depth pavement cores (150-mm diameter) were also obtained adjacent to the square holes to observe the pavement layers and to determine the thickness, bulk specific gravity, and air void content of each layer (Figure 8).

Figure 9 shows the full-depth cores taken (from left to right): inside wheel track, between the wheel tracks, and outside wheel track. All cores showed the following five asphalt pavement layers from top down: new gravel wearing course, old limestone binder course, old gravel wearing course, old slag wearing course, and old limestone binder course. The old limestone binder course underlying the new gravel wearing course had more cavities in the core taken from the inside wheel track compared to the other two cores (Figure 9). Evidently, the inside wheel track was showing more distress compared to the outside wheel track at the time of inspection. More severe stripping was taking place in the inside (left) wheel track of the slow lane probably due to (a) close proximity to the longitudinal center line joint of the PCC pavement where ingress of water from the subgrade is usually high, and (b) increased distance from the pavement base drain at the edge compared to the outside (right) wheel track.

As mentioned earlier, pavement investigation was also conducted in a relatively good area of this project at MP 212.9. Figure 10 shows the westbound lanes which do not exhibit any distress at this time (July 1996). Three holes were cut at MP. 212.9 similar to MP 217.65. Stripping had already initiated in the new gravel wearing course at the bottom. Although the old limestone

Figure 8. Cores taken adjacent to square holes at MP 217.65.

Figure 9. Cores taken at MP 217.65 (from left to right): inside wheel track, between the wheel tracks, and outside wheel track.

binder course was wet to a lesser extent compared to that at MP 217.65, it was stripped badly. The old gravel wearing course was also wet and very friable. It appeared a matter of time before the distress in the form of flushing and potholes would also be observed in this so-called relatively good area. Table 2 gives a summary of observations for each layer in the three holes. Three 150-mm diameter cores were also taken beside the holes at MP 212.9.

Figure 10. General view of the relatively good area of the westbound lanes near MP 212.9.

Table 2. Visual Observations of Holes at MP 212.90 in Westbound Slow Lane

Pavement Layer	Inside Wheel Track (IWT)	Between Wheel Tracks (BWT)	Outside Wheel Track (OWT)
New Gravel Wearing Course	Moist, stripping at the bottom (40%), excess asphalt binder can be seen migrating toward the surface	Observations similar to IWT	Observation similar to IWT
Old Limestone Binder Course	Wet, badly stripped (80%), loss of cavities	Observations similar to IWT except stripping is about 70%	Observation similar to IWT
Old Gravel Wearing Course	Moist to wet, stripped (50%), mix is very friable, can be broken with hand	Observations similar to IWT except the mix is moist	Observation similar to IWT
Old Slag Wearing Course	Moist, minimal stripping	Observations similar to IWT except the mix is moist	Observation similar to IWT
Old Limestone Binder Course	Wet, partly stripped	Observations similar to IWT except the mix is moist	Observation similar to IWT
Concrete	Wet	Observations similar to IWT except the mix is moist	Observation similar to IWT

Test Results

The mix samples obtained by a jack hammer from the top three asphalt courses were placed in sealed containers for determining their moisture contents in the laboratory. Extra mix samples were also obtained to determine the maximum theoretical specific gravity of the asphalt mixes in these three courses. Each of these three courses was also sawed off from the core to determine its bulk specific gravity. In-situ air void contents were then determined from the bulk specific gravity and the average maximum theoretical specific gravity (average of 8 test results).

The percentage of air voids saturated with moisture or water was calculated using the following equation:

$$\%\ Saturation = \frac{\%\ moisture\ by\ weight \times bulk\ specific\ gravity}{\%\ air\ void\ content} \times 100$$

Tables 3 and 4 give the bulk specific gravity, maximum theoretical specific gravity, air void content, moisture content, and percentage of saturation data for the westbound slow lane at MP 217.65 (distressed area) and MP 212.90 (relatively good area), respectively. All three courses are completely saturated with water, which is consistent with the field observations in July 1996. As mentioned earlier, the cyclic pore pressure generated by heavy traffic in these saturated asphalt courses was probably causing severe stripping of the asphalt binder from the aggregate. The calculated saturation levels are generally much more than 100 percent, because some water has been absorbed by the stripped aggregate and also additional voids might have been created by the loss of asphalt binder due to stripping. Since the in-situ air void contents of the new gravel wearing course (placed in 1994) were generally lower than 5 percent, this course was almost impermeable to surface water. Therefore, this course was being stripped from the bottom upwards by the water coming from underneath the pavement due to inadequate subsurface drainage conditions.

Table 3. Density, Moisture and Saturation Data (MP 217.65, Westbound Slow Lane)

Layer	Property	Location		
		Inside Wheel Track (1)	Between Wheel Tracks (2)	Outside Wheel Track (3)
A. New Gravel Wearing Course	Bulk Sp. Gr.	2.362	2.304	2.376
	% Air Voids*	2.1	4.5	1.5
	% Moisture by wt.	1.2	2.6	0.7
	% Saturation	135	133	110
B. Old Limestone Binder Course	Bulk Sp. Gr.	2.416	2.419	2.442
	% Air Voids**	3.3	3.2	2.3
	% Moisture by wt.	1.1	1.3	0.9
	% Saturation	80	98	96
C. Old Gravel Wearing Course	Bulk Sp. Gr.	2.223	2.220	2.240
	% Air Voids***	4.9	5.0	4.2
	% Moisture by wt.	3.2	3.3	3.0
	% Saturation	145	146	160

* Based on an average maximum theoretical specific gravity of 2.413
** Based on an average maximum theoretical specific gravity of 2.499
*** Based on an average maximum theoretical specific gravity of 2.337

Table 4. Density, Moisture and Saturation Data (MP 212.90, Westbound Slow Lane)

Layer	Property	Location		
		Inside Wheel Track (1)	Between Wheel Tracks (2)	Outside Wheel Track (3)
A. New Gravel Wearing Course	Bulk Sp. Gr.	2.349	2.252	2.361
	% Air Voids*	2.7	6.7	2.2
	% Moisture by wt.	1.3	1.7	1.3
	% Saturation	113	57	140
B. Old Limestone Binder Course	Bulk Sp. Gr.	2.453	2.437	2.471
	% Air Voids**	1.8	2.5	1.1
	% Moisture by wt.	1.0	1.1	0.9
	% Saturation	136	107	202
C. Old Gravel Wearing Course	Bulk Sp. Gr.	2.266	2.212	2.240
	% Air Voids***	3.0	5.4	4.2
	% Moisture by wt.	3.2	2.9	2.6
	% Saturation	242	119	139

* Based on an average maximum theoretical specific gravity of 2.413
** Based on an average maximum theoretical specific gravity of 2.499
*** Based on an average maximum theoretical specific gravity of 2.337

General Observations and Recommendations

1. Water and/or water vapor was getting into the pavement structural system from underneath primarily through the longitudinal and transverse joints, cracks in the PCC pavement and the disintegrated concrete itself at some places. With pavement almost saturated the pore water pressure developed by differential thermal expansion and cyclic stresses (compression/decompression) from the traffic ruptures the asphalt-aggregate bond causing stripping. Extensive stripping was observed in the old limestone binder course. It is highly likely that this course was already stripped when the new gravel wearing course was placed in 1994. The moisture or moisture vapor in this old limestone binder course initiated the stripping at the bottom of the new gravel wearing course. If stripping takes place in any layer, the asphalt binder has separated from the aggregate surface allowing the fines to migrate upwards and appear as a white or gray spot. The stripped asphalt binder also starts to migrate upwards causing the flushing of the pavement surface. A pothole then develops in the flushed area which has almost bare aggregates underneath. All typical symptoms of stripping: white or gray spots, flushing, and potholes, were present on this project in the distressed area. Briefly, stripping of the pavement layers underlying the new gravel wearing course had already taken place due to inadequate subsurface drainage conditions. These conditions in turn initiated stripping in the new gravel wearing course (placed in 1994) at the bottom and the stripping was progressing upwards.
2. Although the segment of this project between MP 215.5 and 209.5 is not showing any significant distress at this time, stripping has already taken place in the pavement layers underlying the new gravel wearing course. Therefore, this segment is also expected to develop problems, similar to the distressed segment between MP 215.5 and 218.0, in the near future. The delay in the development of distress at the surface cannot be explained. It could be due to different construction/subsurface drainage conditions which could not be established.

The following recommendations based on the experience of the author were made to rectify the subsurface drainage problem and to reconstruct the asphalt overlays:

1. Mill off all asphalt overlays (about 200 mm) down to PCC pavement. Rubblize the PCC pavement. Place a 100-mm thick layer of asphalt treated permeable material (ATPM) drainage course right over the rubblized PCC pavement. The ATPM should be connected on both sides to the longitudinal edge drains. The ATPM primarily consists of AASHTO No. 57 or 67 aggregate (no fine aggregate) coated with 1-1/2 to 2-1/2 percent asphalt binder. It has been used successfully on I-90 near Erie in similar applications. The structural coefficient of ATPM is believed to be about 0.30. The ATPM should be overlaid with HMA consisting of a binder course and a wearing course of adequate thicknesses to meet the structural design requirements. (Since this investigation, the Pennsylvania Turnpike Commission has undertaken reconstruction of some segments of the Turnpike. The reconstruction involves removal of all HMA courses and the PCC pavement and providing an ATPM at the bottom of new HMA courses.)
2. Consideration should be given to the use of 1-1/2% of hydrated lime (by weight of aggregate) as an antistripping agent in all HMA mixes which are used on the Turnpike in situations similar to this project. Whereas the use of hydrated lime can not be a substitute for proper subsurface and/or surface drainage system, it can increase the resistance of the HMA mix to stripping. AASHTO T283 (modified Lottman test) with a freeze and thaw cycle should be used to determine the resistance of the HMA mixes to moisture- induced damage.

INTERSTATE 40 IN OKLAHOMA

This Interstate 40 overlay project in Oklahoma completed in 1990 was comprised of the following:

- Removal of 90 mm of existing asphalt courses by cold milling
- Placing 70 mm Type "F" mix binder course
- Placing 20 mm open graded friction course (OGFC)

The OGFC paving on the westbound (W.B.) lanes was done during the cool season in October 1990. Project inspection in November 1990 indicated that Type F mix both in westbound (W.B.) and eastbound (E.B.) lanes was taking on water when it rained. When it was observed during the construction of Type F in W.B. lanes that this mix was not impervious to water, it was decided to use dense-graded Type E mix (in lieu of OGFC) over Type F in E.B. lanes. However, Type E mix was not really a dense-graded mix (it is in-between OGFC and a dense-graded mix) and it could be pervious to water. Type F binder course mix was also a coarse-graded mix proposed for improved rut resistance. Table 5 gives the gradation of both Type F and Type E mix used. It is very important to have an impervious hot mix asphalt (HMA) layer underneath OGFC so that water can be drained off the mainline pavement and does not penetrate down the pavement structure.

This project was investigated in September 1991 (about one year after completion). The following observations were made:

Severe potholing was occurring on the outside wheel track of the W.B. slow lane (Figures 11 and 12). Type F mix was stripping badly at numerous locations and patching was being done. Although it had not rained for 3-4 days, free water could be seen in the potholes. It appeared that the F mix was taking on water through OGFC, and this water was blocked by the impervious shoulder thus causing a "bath tub" effect. This segment of I-40 did not have edge drains. Most potholes were in the outside wheel track area which was continuously fed with water from the remaining width of the pavement towards the median. Therefore, the bath tub effect would be accentuated near the pavement edge due to cross slope. Heavy truck tires had created water pore pressure in the F mix and caused stripping of the asphalt binder from the aggregate. All classical three stages of stripping were evident on the road surface (Figure 13): (i) deposition of water transported aggregate fines or dust from partially stripped aggregate onto the road surface, (ii) migration of asphalt binder to road surface or flushing, and (iii) development of potholes in the flushed areas.

Table 5. Gradation of Oklahoma Type F and E Mixtures Used on Interstate 40

Sieve Size (mm)	Percent Passing	
	Type F	Type E
25	100	--
19	90	--
12.5	75	100
9.5	--	99
4.75	36	50
2.36	29	27
1.18	23	19
0.6	18	15
0.3	12	10
0.15	6	4
0.075	4	3

Figure 11. Development of potholes primarily in the outside wheel track of I-40 in Oklahoma.

There was no clear pattern of potholing in the W.B. lanes. Potholes were observed on summits or valleys, and cuts or fills. Apparently, F mix was stripping in areas which had relatively low density or high air void content (for example, in segregated areas).

Figure 12. Potholing on I-40, Oklahoma.

Visual observation of E.B. lanes did not show any major distress at the time of inspection. Possibly, Type E mix was not allowing as much water into F mix as the OGFC used in W.B. lanes. Some patches were seen in the inside wheel track of the E.B. slow lane. Stripping might have been initiated (to a lesser degree) in the F mix of E.B. lanes, but signs of stripping were not yet apparent on the surface. Rutting appeared to be about 10 mm in the slow lane of E.B. lanes. It was recommended that some cores be taken in the E.B. slow lane and examined for stripping.

The roadway was sampled with a jack hammer as well as a coring device. No moisture content determinations were made on this project. Figure 14 shows a very open F binder mix underneath the OGFC. In many cases, F mix crumbled and OGFC stayed intact (Figure 15). Therefore, the primary cause of the stripping problem being experienced

Figure 13. Three stages of stripping: white stains, flushing, and pothole (I-40).

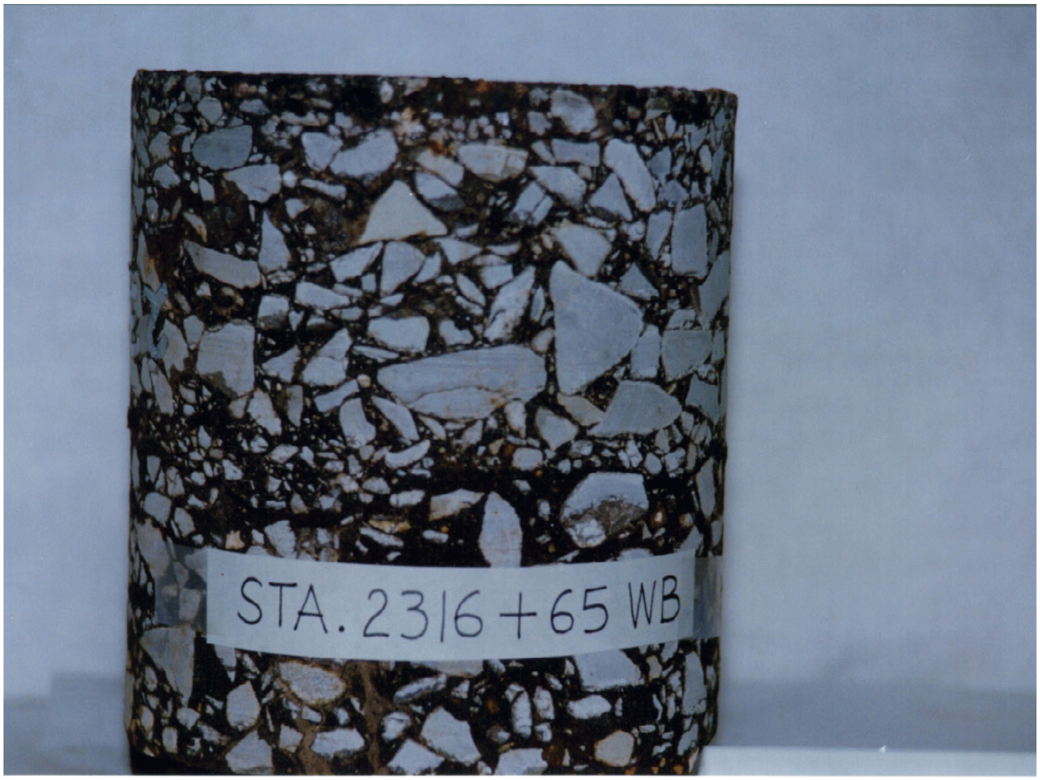


Figure 14. Pavement core showing an open, coarse-graded F binder mix underlying the OGFC (I-40).

Figure 15. Stripped F binder mix (right) which crumbled on coring with an intact OGFC layer (I-40).

on this project was the selection of a coarse-graded, pervious F binder mix underneath OGFC in a pavement which did not have any edge drain. The "bath tub" effect created by this situation caused the F mix to strip badly due to pore pressure created by the traffic. It was recommended to use a relatively impervious surface course underneath the OGFC.

WILL ROGERS PARKWAY IN OKLAHOMA

This asphalt overlay involved milling the existing 20 mm open graded friction course (OGFC) off the existing Oklahoma B mix and replacing it with 25 mm thick dense-graded E mix wearing course (gradation similar to that shown in Table 5). After the paving was completed in June 1992, the pavement started to show distress in various locations in July (within one month). The project was investigated in July 1992.

The following visual observations were made during the inspection:

1. Most of the potholes were occurring in the inside wheel track of the eastbound (E.B.) and westbound (W.B.) slow lanes (Figures 16 and 17). This type of premature pothole pattern (on the wheel tracks of a slow lane) is usually associated with stripping of underlying hot mix asphalt (HMA) layer(s).
2. Rutting was also occurring in several areas in the inside wheel track of the E.B. and W.B. slow lanes. This type of premature rutting pattern (on the wheel tracks of a slow lane) can also be associated with stripping of the underlying HMA layer(s) which otherwise comprise of a stable mix. Potholes were expected to develop in those areas soon.
3. Although it had not rained for more than two days prior to this inspection, free water was observed to be coming out of thermal cracks in the shoulder area (Figure 18), from the edge of the raised grassy median (Figure 19), and from the pavement/shoulder joint (Figure 17). This pavement did not have any edge drain to intercept subsurface water.
4. Although the cracks from the underlying B mix or the concrete pavement had not reflected yet through the new E mix, these cracks could be located at some places from the traces of white stain lines in the new E mix. If the underlying HMA layer(s) is stripped, water will bring up the fines from the stripped (bare) aggregate. Apparently, water was coming up through these cracks and was getting dried up at the surface leaving the residue of fines.
5. Big white-stained patches (Figure 20) could be seen near the potholed areas. No flushing of the pavement was observed. Typically, when the stripping is initiated in the underlying layer(s), white stains appear first (due to migration of fines from the stripped aggregate upwards with water), flushing or bleeding appear next (due to migration of stripped asphalt binder upwards), and the potholing occurs last in the flushed area (this sequence was observed in the first two case histories. Since no flushing was observed in this case, it indicated that the underlying B mix had already stripped substantially and had lost most of the binder prior to the placement of E mix.
6. The contractor had placed two long patches at one location prior to inspection to repair a large potholed area. One patch was placed after removing the E mix and the deteriorated (stripped) B mix. The other patch was placed after removing the E mix only. The latter patch had already started to fail because it was underlain by deteriorated (stripped) B mix as confirmed later.
7. A jack hammer was used during the inspection to remove the HMA pavement layers for observation without adding any water (Figure 21). First the E mix was removed. It appeared satisfactory. Then the B mix layer was removed. The top half of the B mix layer was stripped severely (Figure 22). The mix was very friable (no cohesion due to lack of asphalt binder) and it contained excessive visible moisture. The concrete pavement underneath was also wet. Average moisture (water) content in the B mix was determined to be 2.76% when the samples taken by jack hammer were sealed and tested in the

Figure 16. Potholing in the inside wheel track of slow lane.

Figure 17. Potholes in the inside wheel track of slow lane (another location).

Figure 18. Water coming out of thermal cracks.

Figure 19. Water from the raised grassy median.

Figure 20. Big white-stained patches near potholed areas.

Figure 21. E mix and B mix layers removed by jack hammer.

Figure 22. Bottom of stripped B mix layer.

laboratory. The average air void content of the B mix layer was determined to be 7.1% based on the density of seven cores. This means that the air voids in the B mix were saturated 89.4% with moisture (water).

The lower half of the B mix was stripped to a lesser extent. It appears that the stripping in the B mix layer was initiated at its top and progressed downwards. This downward type of stripping pattern is associated with the presence of an OGFC at the top as observed in several southeastern states. It has been hypothesized that the OGFC retains moisture for a longer time and does not dry out after rain as fast as a conventional dense graded HMA surface. The water in OGFC is also pressed into the underlying course by the truck tires initiating the stripping which progresses downwards.

8. The E mix surface was almost impermeable to surface water as indicated by the water (from the coring operations) standing on the surface for a long period of time.

The following conclusions were drawn from the preceding observations of the pavement surface, exploration of the HMA layers with a jack hammer (without addition of any water), and the coring operations:

1. B mix layer was already stripped when the dense-graded E mix was placed over it after milling off the existing OGFC. That is why the overlay started to develop potholes within a month.
2. Stripping in the B mix was initiated in the past by the presence of the OGFC at the top (based on experience in several southeastern states), and the water or moisture coming through the cracks and joints of the pavement structure and by seepage from the raised grassy median. Since there were no edge drains on either side of the pavement, there was no outlet for the subsurface water. This quite likely accelerated the stripping phenomenon in the B mix.
3. Rutting and/or potholes were likely to be developed wherever the B mix had stripped excessively in spite of the new E mix layer at the top.

4. Patch repairs were more likely to be successful if the deteriorated (stripped) B mix was also removed and replaced with a dense-graded B mix, and a positive subsurface drainage system was installed.

HUME HIGHWAY IN NEW SOUTH WALES, AUSTRALIA

An existing asphalt section of the 4-lane Hume Highway south of Sydney in New South Wales was overlaid in May/June (winter in Australia) 1993. As shown in Figure 23, the asphalt overlay consisted of the following:

- 80 to 120 mm (variable to regulate slope) of AC 28 dense-graded binder course
- 35 mm of AC 14 dense-graded surface course
- 30 mm of open graded friction course (OGFC)

AC 28 and AC 14 denote the maximum nominal sizes of 28 mm and 14 mm, respectively, of the two dense-graded mixes used. Table 6 gives the mix composition of all three mixtures used. Coarse aggregates consisted of basalt; some crushed river gravel fines were used.

A liquid antistripping agent was used in Bitumen Class 320 (viscosity of 320 ± 60 Pa.s at 60°C). All the mixes were found to easily satisfy the retained tensile strength of 80% minimum using ASTM D 4867 (Modified Lottman), and this was consistent with a long history of good performance of these materials.

The southbound lanes of the Hume Highway started to develop potholes in February 1995 (during the second summer some 20 months after construction). The potholes were occurring in the wheel tracks of the slow lane. Both the southbound and northbound highways comprise a 3-m emergency shoulder, two 3.5-m lanes, and a 1-m shoulder. The pattern of potholes (which

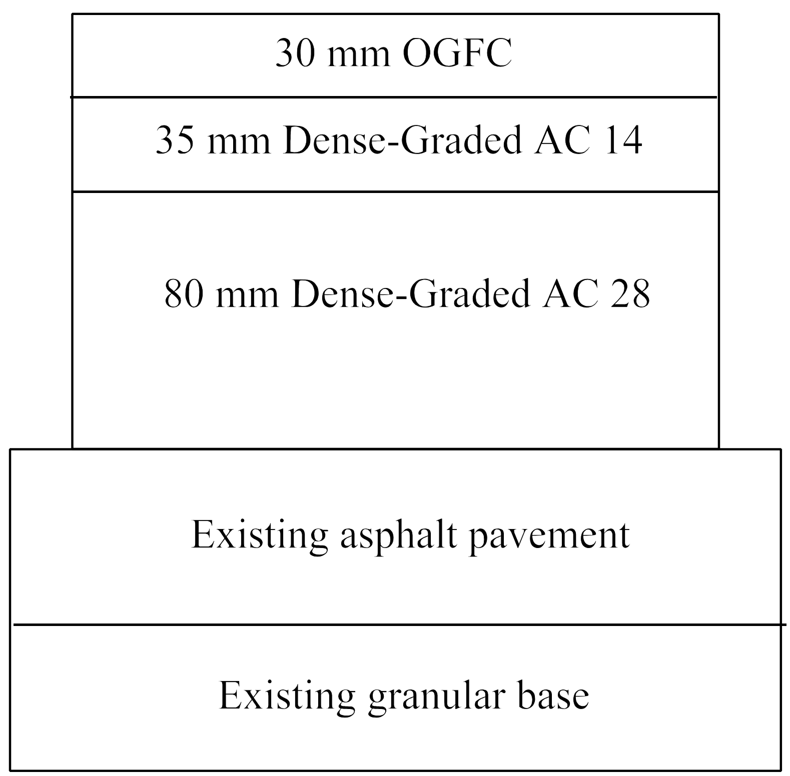


Figure 23. Courses used in new asphalt overlay on Hume Highway.

Table 6. Composition of Mixes Used on Hume Highway

Property	Dense-Graded AC 14 Mix	Dense-Graded AC 28 Mix	Open-Graded Friction Course OG 14
Percent passing,			
37.5 mm	--	100	--
26.5 mm	--	97	--
19.0 mm	100	81	--
13.2 mm	96	67	100
9.50 mm	80	62	93
6.70 mm	64	57	61
4.75 mm	55	51	41
2.36 mm	40	42	17
1.18 mm	29	29	12
0.6 mm	21	20	10
0.3 mm	11	12	7
0.150 mm	5	7	5
0.075 mm	4.3	5.5	4
Asphalt content	5.2	4.2	5.2
Air voids*, %	4-7	4-7	18-23
VMA*, %, min.	15	13	--

* Specimens compacted by Modified Hubbard-Field Procedure

required frequent patching) can be seen in Figures 24 and 25. First a white stain would appear on the surface of the OGFC, followed by a circular pattern of alligator type fatigue cracking (as shown in Figure 26), and then a pothole.

In March 1995, test holes (approximately 400 mm square) were excavated in the asphalt pavement with a jack hammer (Figure 27), and the excavated material collected for testing. Samples were collected from each asphalt layer (OGFC, AC 14, and AC 28) and stored in sealed plastic bags prior to moisture determination and visual evaluation to determine the extent of stripping. Dry excavation methods were used to facilitate moisture content determination. Tests holes were excavated both at sites exhibiting failure and about 15 m away at sites that had no visible sign of failure. A limited number of test holes were also excavated in the 3-m wide shoulder to obtain the moisture profile within that undamaged portion of the pavement.

A 150-mm diameter core was taken immediately adjacent to each test hole, which were located between and within the wheel path, to determine the in-place air voids in all courses.

Figure 28 shows typical moisture contents in OGFC, AC 14, AC 28, and existing asphalt course at four locations. Designation C such as Site 7-C stands for test hole in the center of the lane (between the wheel paths). Designation O such as Site 7-O stands for test hole on the wheel path. There was no significant difference in moisture content of the materials extracted from test holes at the failed and adjoining non-failed sites, indicating the water ingress preceded, and was not as a consequence of, the failure.

Figure 24. Pattern of potholes and patch repairs in the southbound slow lane of Hume Highway.

Figure 25. Potholes in the southbound slow lane of Hume Highway (another location).

Figure 26. Stages of pavement distress: white stains, alligator cracks, and pothole.

Figure 27. Excavation of each asphalt layer with a jack hammer.

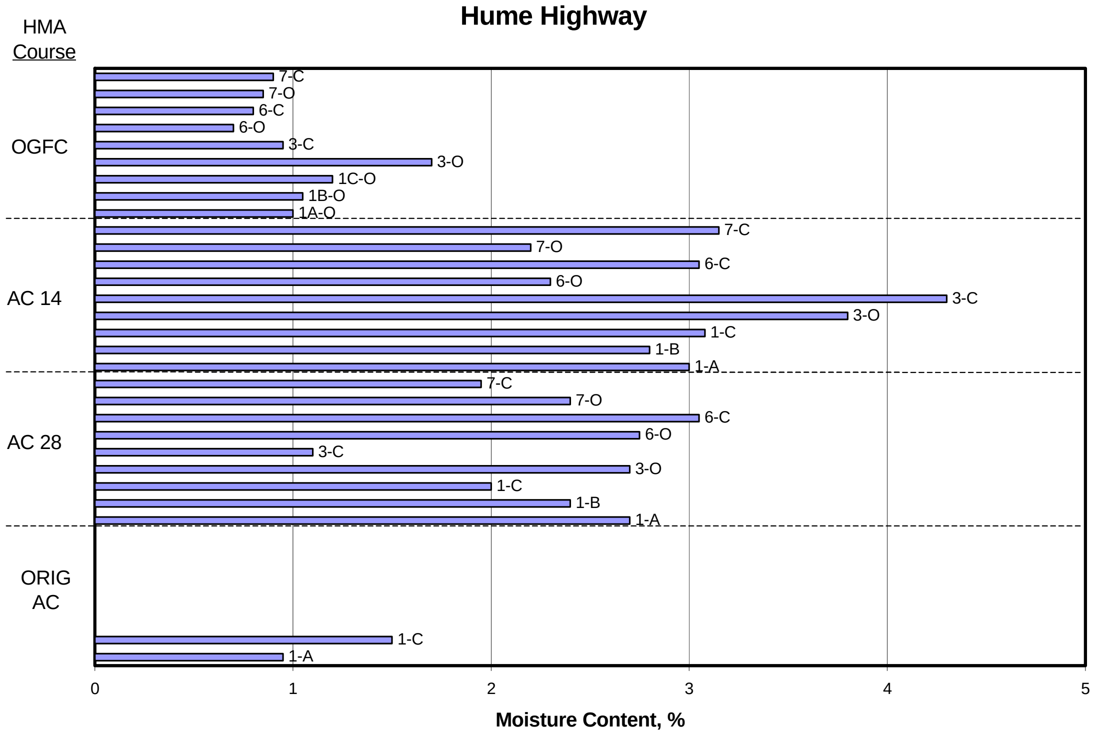


Figure 28. Moisture content profile at Site 1, 3, 6, and 7.

Figure 29 shows the relative comparison of moisture contents in OGFC, AC 14 and AC 28 courses obtained in nine test pits. The following observations can be made.

1. Generally, AC 14 which underlays the OGFC has higher moisture content than AC 28. Figure 30 clearly shows a very wet AC 14 course just below the OGFC in the test hole.
2. Moisture contents are slightly higher at locations between the wheel path compared to the locations on the wheel path. This probably resulted from relatively lower air voids in the wheel path resulting from densification by traffic.

Table 7 summarizes the pavement test data and visual stripping evaluation by giving the average moisture content in all pavement layers both on the traffic lane and shoulder. Similar to the case history of the Pennsylvania Turnpike, the average degree of saturation was also calculated from moisture content, bulk specific gravity of the HMA course, and air voids.

The following observations can be made:

1. The moisture profile shows decreasing moisture contents from surface downwards. However, the air voids in both AC 14 and AC 28 are almost completely saturated with moisture.
2. The existing asphalt course was not significantly stripped. Only AC 28 and AC 14 and bottom 1/3 of the OGFC were stripped in the slow traffic lane. Figure 27 shows a piece of badly stripped AC 28.
3. Both AC 14 and AC 28 courses did not strip in the shoulder obviously due to reduced saturation and lack of traffic loading.

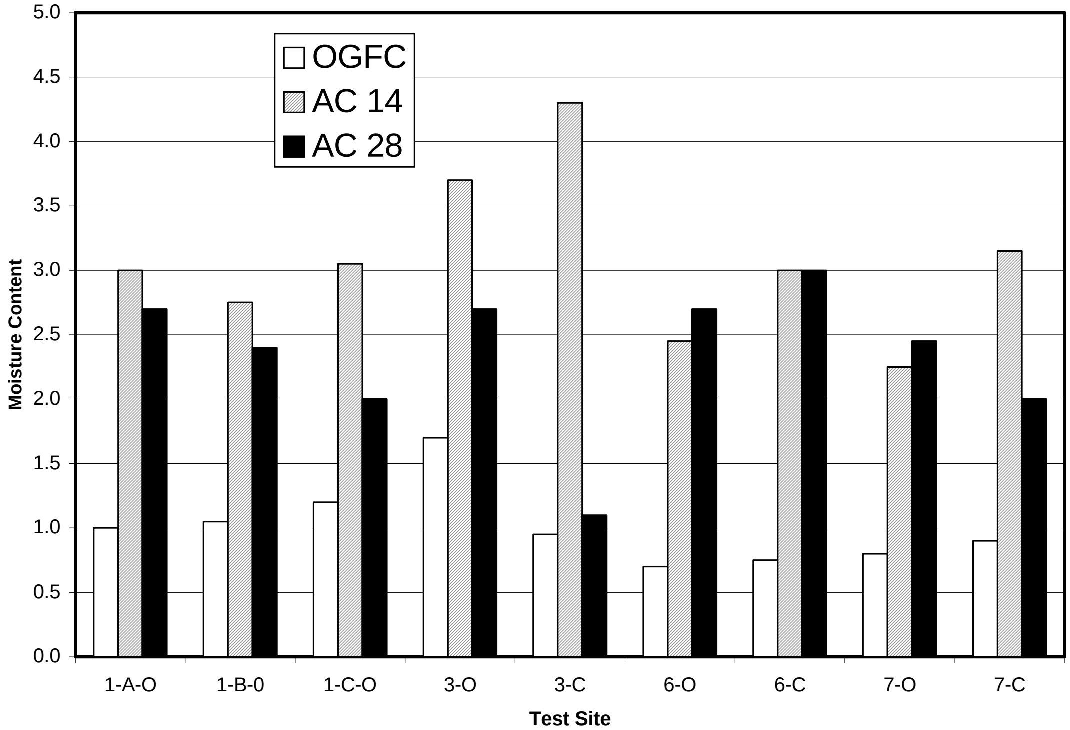


Figure 29. Comparative moisture contents at Sites 1, 3, 6, and 7.

Figure 30. Test hole showing a very wet AC 14 course just below the OGFC.

Table 7. Typical Pavement Moisture Content Profile, Degree of Saturation, and Extent of Stripping on Hume Highway

Pavement Layer	Shoulder		Slow Traffic Lane				
	Average Moisture Content	Stripping?	Average Moisture Content	Stripping?	Average Bulk Specific Gravity	Air Voids, %	Saturation, %
OGFC	2.2	Only bottom one-third	1.0	Only bottom one-third	N/A	N/A	N/A
AC 14	2.0	No	3.0	Yes	2.318	7	99
AC 28	0.8	No	2.5	Yes	2.376	6	99
Existing Asphalt Concrete	1.2	No	1.5	No	N/A	N/A	N/A
Existing Granular Base	N/A	--	4.0	--	—	—	—

N/A - Not available

After the preceding pavement evaluation in March 1995, and extensive patch repairs, a chip seal was applied in May 1995 over the most distressed segment of the project. The chip seal was an interim attempt to hold the situation while a more robust remedy was designed. The hope was that the seal applied to the OGFC may reduce the infiltration of surface water, and permit the escape of moisture vapor via the remaining voids in the OGFC.

Both authors investigated the project in March 1996. More test holes were excavated with a jack hammer in the slow lane and shoulder of the distressed southbound lanes. A milling machine was also brought (Figure 31) to mill off the asphalt overlays so that all courses could be evaluated visually. The test data and observations were similar to those in March 1995. Free moisture was visible in AC 14 just below the OGFC at the edge of the milled trench (Figure 32). Both AC 14 and AC 28 mixes were badly stripped (Figure 33).

The following general observations were made by the authors after the inspection:

- Moisture probably entered the AC 14 and AC 28 courses by the mechanisms described in the following section. The OGFC had about 18 to 20% air voids when constructed and this served as a reservoir in periods of rainfall.
- The AC 14 when constructed in winter had air voids between 8 to 10 percent. The OGFC was placed immediately following the AC 14 course before it was trafficked. Hence the AC 14 layer was not sealed (surface capillaries were not closed by traffic) and densified under traffic.
- No seal was provided at the bottom of the OGFC and, therefore, moisture continued, by the mechanisms described in the following section, to penetrate the interconnected voids of AC 14 and AC 28 courses until they became saturated.
- The heavy traffic loads in the slow lane created cyclic pore pressure in the saturated material that physically scoured the asphalt binder from the aggregate and thus stripping resulted. It is recalled no significant stripping was observed in the shoulder area.
- The white stains on the surface probably resulted from the upward migration (induced by moisture) of the fines after asphalt binder had stripped off the aggregate surface.
- Alligator type fatigue cracking in the OGFC surface most likely resulted from the loss of support from stripped AC 14 and AC 28 courses, and this led to the development of potholes.

It was questioned as to why potholes were not developing to the same extent in the northbound lanes of the Hume Highway, which were constructed at the same time, with same materials, and to same specifications. Hourly traffic data was requested for both southbound and northbound lanes. It was noted that the peak traffic (about 1000 vehicles per hour) occurred on the southbound lanes in late afternoon when the pavement temperature was highest up to 60°C in summertime at this location. Moisture vapor buildup in the pavement was also at a peak and water had been seen oozing out of asphalt pavement in late afternoons in earlier investigations (1). On the northbound lanes the peak heavy vehicular traffic occurred in the early hours of the morning, before sun-up, thus the pavement was considerably cooler and stiffer and had relatively lower moisture vapor buildup. High pavement temperature is believed to be an important element in the observed stripping. It is logical that the adhesive strength of the binder at the aggregate interface is reduced at high temperature rendering it more prone to mechanical scouring.

Figure 31. Cold milling in the slow lane and shoulder area to evaluate the condition of asphalt layers.

Figure 32. Wet AC 14 course just below OGFC at the edge of the milled trench.

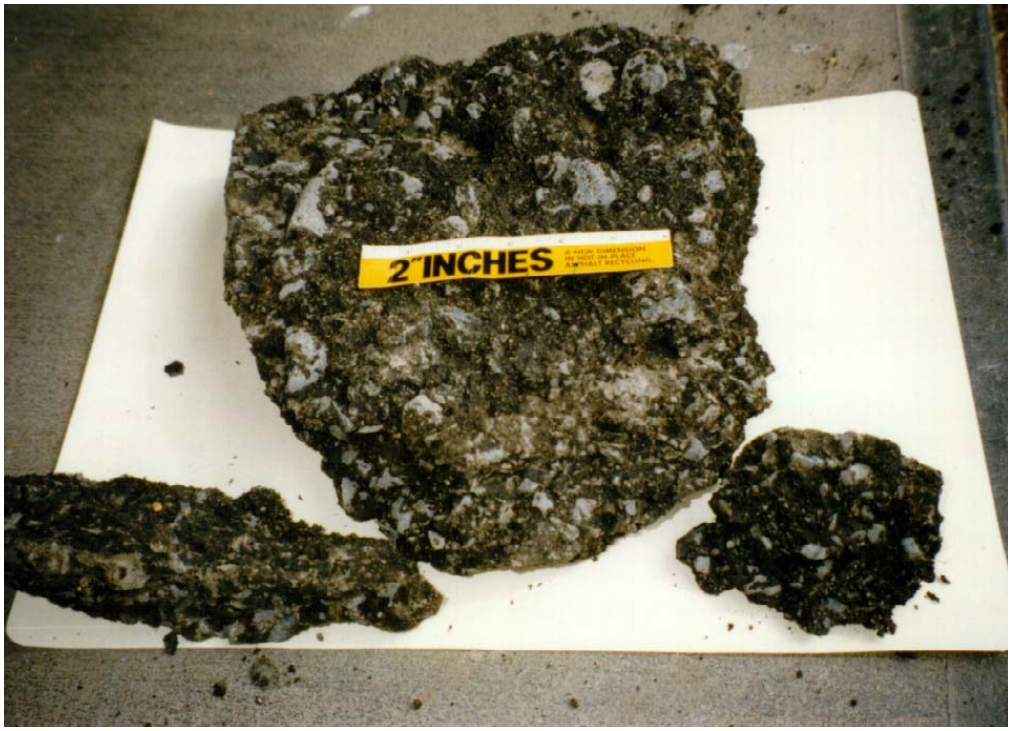


Figure 33. Badly stripped AC 28 and AC 14 courses.

HYPOTHESIS FOR ASPHALT STRIPPING FAILURE MECHANISM

The authors do not anticipate substantial disagreement with their fundamental premise that saturated HMA layers will, under extremes of loading and at high pavement temperatures, be gravely at risk of stripping as a result of the mechanical scouring of the binder film from the aggregate surface caused by high pressure and rapid movement of moisture. Obviously, mixes containing stripping prone aggregates (such as some siliceous aggregates) are at greater risk under these conditions.

Literature rarely if ever reports the moisture content of stripped asphalt pavements. The authors suspect that we may have often overlooked pavement saturation as a principal contributor to stripping failures. If we accept this premise a clearer understanding of the factors that contribute to the saturation of asphalt layers is considered vital.

There are numerous examples (including the last three case histories) of stripping that occurred in dense graded HMA following an OGFC overlay. The following hypothesis attempts to explain the observed failure mechanism.

A typical dense-graded HMA wearing course when constructed can have as much as 8 percent air voids. However, traffic loading generally reduces the air voids to 4-5 percent during the first 2-3 years thus eliminating the interconnected air voids and making the mix almost impermeable to surface water. The direct kneading action of the traffic especially during summer also seals the surface of the wearing course. Besides high air void content, there are three essential ingredients to promote stripping:

- the presence of water

- high stress
- high temperature

It must be assumed that some moisture will always be present in HMA (other than in arid conditions perhaps). It is hypothesized that in well-constructed dense-graded wearing courses the presence of water is limited to a volume well below saturation. Certainly in periods of rainfall some moisture ingress may occur. Experience suggests the ingress of moisture is balanced by the egress of moisture in the form of vapor as shown in the sketch in Figure 34 (after Rickards, 4). If the concept of asphalt mat "breathing" did not hold true we would expect considerably more stripping problems.

Excess moisture sufficient to cause saturation in heavily trafficked asphalt pavement, may result from moisture being fed from underneath in the form of moisture vapor due to inadequate subsurface drainage (example, the Pennsylvania Turnpike case history).

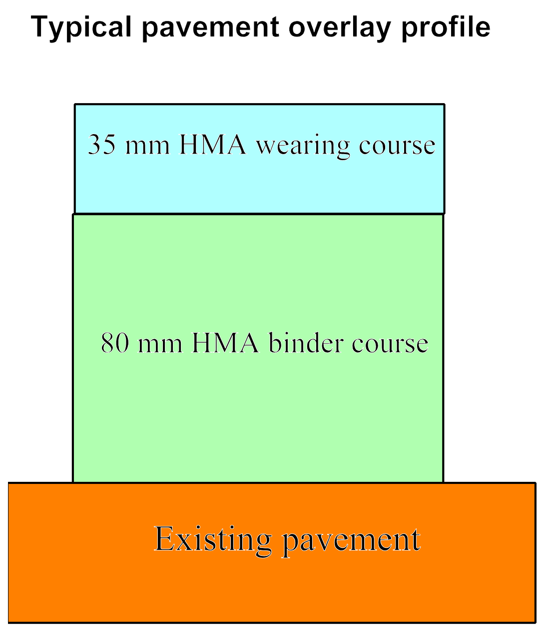
Also, excess moisture sufficient to cause saturation in non- trafficked asphalt pavement, such as on the flanks of airport pavements, may be evident (example, Sydney's Mascot airport). In this case stripping was observed in HMA not immediately within the aircraft wheelpaths. It is postulated the surface of the dense-graded HMA was not sealed by trafficking, and saturation occurred by the thermal pumping mechanism shown in Figure 36 (after Rickards, 4). Stripping is again believed to be a mechanical failure resulting from the combination of hydraulic stress generated by a change in vapor pressure with temperature (typical diurnal temperature range at Mascot 20°C to 60°C), and from the passage of remote aircraft gear which induce a large deflection bowl.

The conditions that occur when a fresh dense-graded HMA course is overlaid by an OGFC are illustrated in Figures 35 and 37 (after Rickards, 4). In such conditions the permeability of the dense graded HMA course is not significantly reduced with time due to the absence of kneading action of traffic and densification. Compaction by traffic is diminished because (a) tire load stress is dissipated by the OGFC, and (b) the temperature of the dense-graded HMA course is generally 5-10°C lower.

It is hypothesized, in wet conditions heavy traffic repetitions impart considerable compression and relaxation cycles within the dense-graded HMA course underlying the OGFC. In the compression phase, air in the HMA course is expelled. As the material relaxes, a partial vacuum is created by the displaced air, and any available water is sucked into the mat. The pavement is therefore acting as a pump and it is quite conceivable the entire mix will become saturated. The issue is exacerbated by the available water and hydraulic head. Normal runoff would be about 1-2 mm deep, the OGFC provides 20-30 mm head depending on its thickness.

The preceding hypothesis is explained further in Figures 34 through 37. Figures 34 and 35 depict typical time/moisture profiles in dense-graded HMA courses without and with OGFC, respectively. Figures 36 and 37 show schematic representation of moisture movement in dense-graded HMA courses due to thermal pumping without and with OGFC, respectively.

Obviously, the hypothesis illustrated in these figures need to be validated in the field using dry sampling methods such as a jack hammer or coring with dry ice as a coolant.

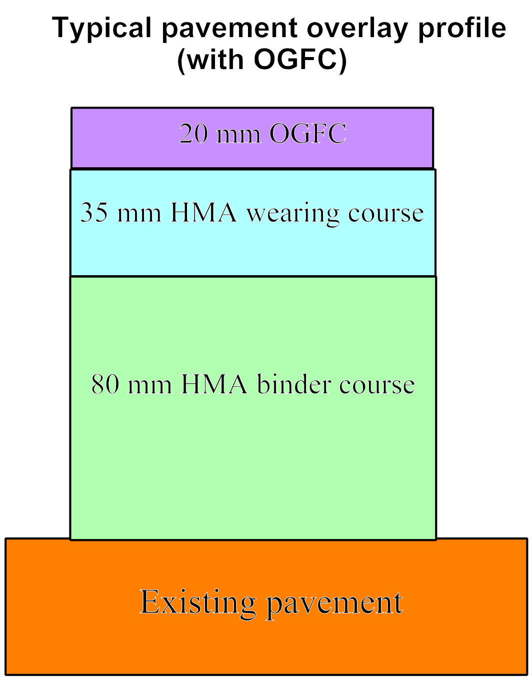


IMMEDIATELY POST CONSTRUCTION
- Surface & mix slightly permeable
- Moisture ingress & accumulation in capillaries relatively slow
- Surface drying rapid due to traffic/heat
- Liquid ingress balanced by vapour egress

SOON AFTER TRAFFICKING
- Surface permeability reduces rapidly due to capillary closures by tire kneading, dust and oil
- High surface temperature promotes vaporization
- Vapor can be expelled by temporary rupture of hot film

IN SERVICE
- Mix densifies and becomes virtually impermeable in location of high stress (wheelpaths)
- The absence of moisture is a critical component in the avoidance of stripping -i.e., high temperature, high stress, is not an issue without moisture

Figure 34. Typical time/moisture profile in asphalt overlay without OGFC (after Rickards, 4).



IMMEDIATELY POST CONSTRUCTION
- Surface, mix, & interface slightly permeable
- Interface drying very slow due to absence of traffic and reduced temperature
- Moisture ingress & accumulation in capillaries is relatively rapid
- Moisture ingress is accelerated by pumping
- Moisture ingress is not balanced by vapor egress

SOON AFTER TRAFFICKING
- Permeability does not significantly reduce
- No capillary closures by tire kneading, dust, and oil
- Pumping is relatively continuous, fed by the long term moisture reservoir at interface
- Lower mix temperature inhibits vaporization
- Long term mix saturation probably inevitable

IN SERVICE
- Mix densification slowed because of lower temperature regime
- Long term permeability in location of high stress
- Saturation, high stress, high temperature -all the critical components of stripping are present

Figure 35. Typical time/moisture profile in asphalt overlay with OGFC (after Rickards, 4).

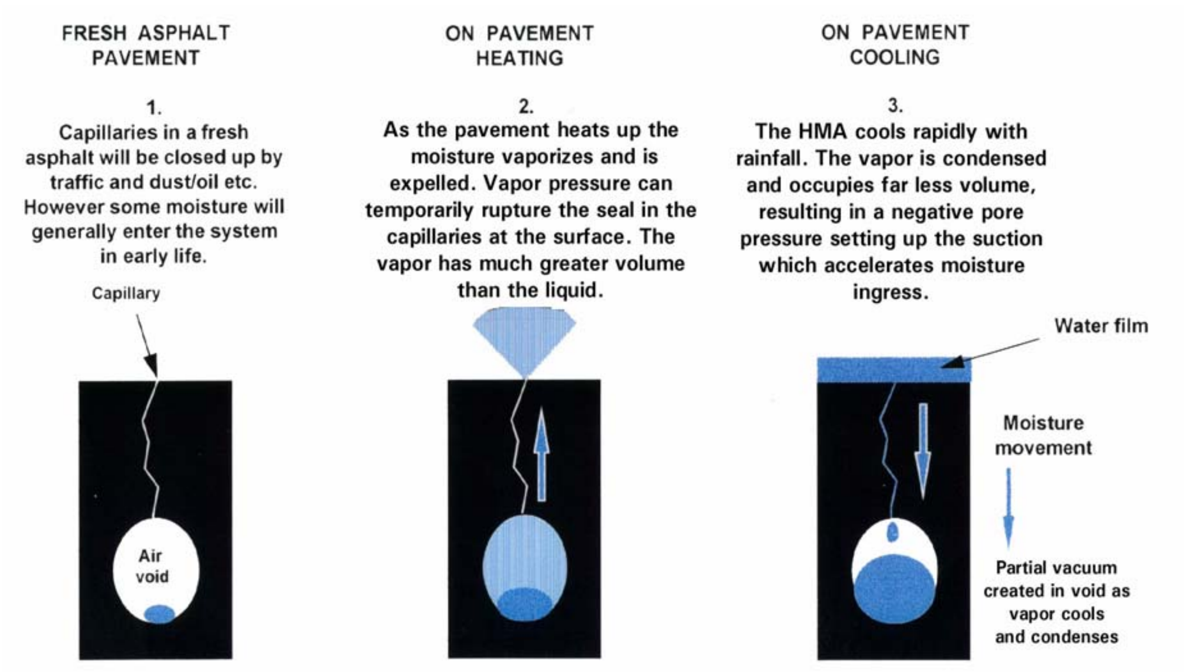


Figure 36. Schematic representation of moisture movement due to thermal pumping, dense graded asphalt wearing course (after Rickards, 4).

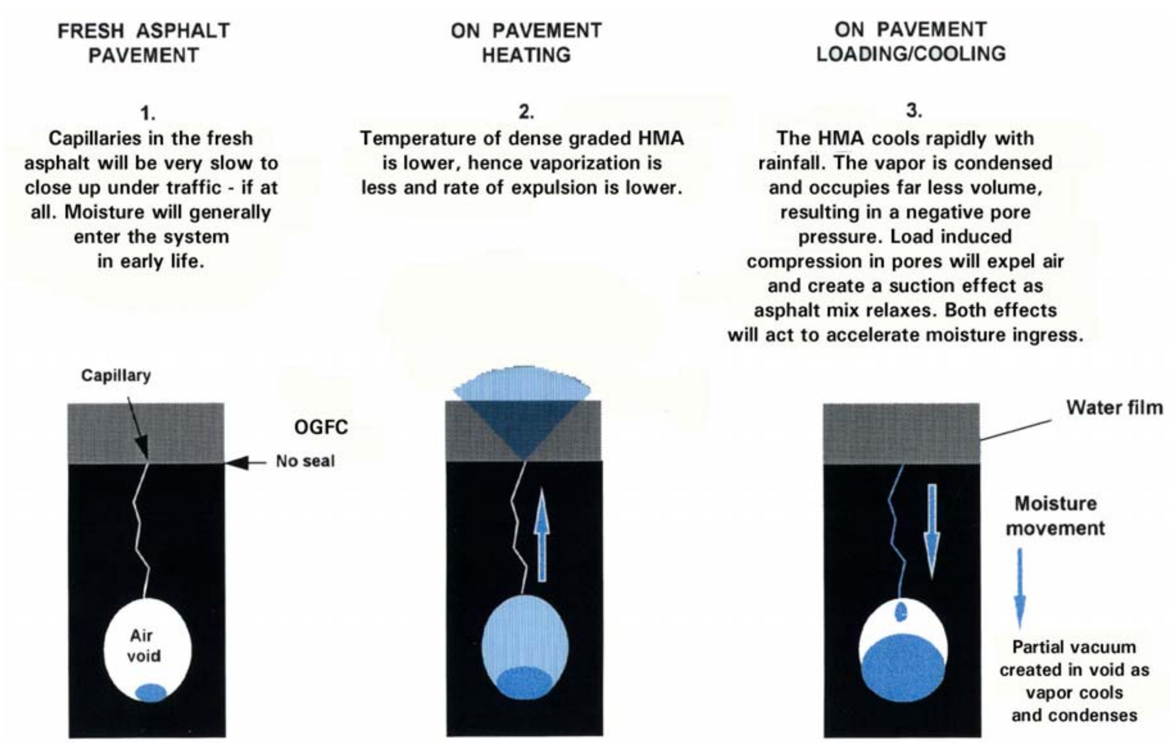


Figure 37. Schematic representation of moisture movement due to thermal pumping, open graded friction course (after Rickards, 4).

OBSERVATIONS AND RECOMMENDATIONS

The following observations are made and recommendations made by the authors from the preceding case histories and the review of literature (5-32):

- It is a fundamental tenet of practicing pavement engineers that three things are vital for pavement performance: drainage, drainage, and drainage. Stripping of asphalt courses will not occur in absence of moisture and moisture vapor.
- The case studies presented identified saturation of asphalt layers by various mechanisms. In each case it is reasonably concluded that saturation is the cause of the problem; stripping is the outcome.
- The degree of saturation of the pavement and asphalt layers is a critical element in the appraisal of stripping failures. Forensic examinations of failures should include a measure of the moisture conditions in failed and non-failed sections of each project to ascertain the degree of saturation in each pavement layer.
- Various mechanisms that explain the saturation process in the asphalt courses have been presented.
- If subsurface drainage of the pavement is inadequate, moisture and/or moisture vapor can move upwards due to capillary action and saturate the asphalt courses.
- Thermal pumping of moisture may occur if trafficking does not reduce the permeability of typical dense-graded HMA, and saturation may follow.
- If saturation exists then stripping is highly likely and is caused by the mechanical scouring of the binder from the aggregate surface due to extreme cyclic pore water pressure generated by heavy traffic. The potential for premature stripping is enhanced further if the HMA mixture consists of a stripping prone aggregate.
- An asphalt treated permeable material (ATPM) base course is recommended at the bottom of the asphalt pavement to intercept moisture and/or moisture vapor. The ATPM should be connected to edge drains on both sides to provide a positive drainage.
- Prior to the application of an open-graded friction course (OGFC) as a wearing course the following are the recommended treatments to minimize saturation in the underlying asphalt course(s):
  (a) Delay the placement of OGFC for two summers if the underlying HMA course has excessive air voids (more than six percent) so that the surface of the underlying mix is effectively sealed by traffic to be practically impermeable to water residing in the OGFC.
  (b) If the placement of OGFC cannot be delayed due to project logistics or safety considerations, apply a uniform emulsion fog seal (use a slow-setting emulsion diluted 50% with water) to completely fill the surface voids just prior to the placement of OGFC.
  (c) Use a relatively fine-graded surface course mix with not more than 12.5 mm maximum nominal size underneath OGFC. The evidence suggests coarse-graded mixes are more permeable.
  (d) Use an “effective” antistripping agent in the underlying surface course mix. The Georgia Department of Transportation has used hydrated lime with success in such applications.
- The pavement design engineer should evaluate the condition of all existing pavement courses in terms of stripping and drainage before deciding about the depth of milling and/or the selection of new asphalt overlays (both type and thickness). Quite often, stripping is not apparent around the surface of the pavement core. Each course should be separated by sawing, slightly warmed (not to exceed 40°C to avoid recoating), and crumbled so that the loose asphalt mix can be examined for stripping. For major projects, it may be prudent to obtain the moisture profile of the pavement (using a jack hammer or coring with dry ice) similar to what was done in the case histories.

- There is a need to develop a reliable and realistic laboratory test method to predict moisture susceptibility of HMA mixtures. It was observed in these case histories that the asphalt pavements were near 100% saturated with water (not 55-80% saturated as specified in ASTM D4867 or AASHTO T283) and the cyclic pore pressure generated by the traffic mechanically scoured the asphalt binder off the aggregate surface. A laboratory test procedure which simulates such conditions will be more realistic. A similar procedure was recommended by Jimenez (33) which involved submerging the specimens in water and applying repeated pulses of water pressure. Tests similar to the SHRP-developed ECS (Environmental Conditioning System), in which specimens can be tested under saturated conditions, and wheel tracking type test (such as Hamburg) also have potential. Validation of any new test procedure should be done on short test pavements which are intentionally saturated with water by designing an inadequate drainage system.

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